REPORT DOCUMENTATION PAGE			*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE ***(DD-MM-YY)***	**2. REPORT TYPE**	**3. DATES COVERED** ***(From - To)***
21-10-16	Conference Proceedings	10/2015 – 03/2016

4. TITLE AND SUBTITLE	
Which eye tracker is right for your research? Performance evaluation of several cost variant eye trackers	**5a. CONTRACT NUMBER** FA8650-14-D-6501-0009
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Gregory Funke[1], Eric Greenlee[2], Martha Carter[3], Allen Dukes[1], Rebecca Brown[4], Lauren Menke[4]	**5d. PROJECT NUMBER**
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER H0HJ (53290813)
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) [1]Air Force Research Laboratory, Wright-Patterson AFB, OH; [2]Texas Tech University, Lubbock, TX; [3]Miami University, Oxford, OH; [4]Ball Aerospace & Technologies Corporation, Fairborn, OH	**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Air Force Materiel Command Air Force Research Laboratory 711th Human Performance Wing Airman Systems Directorate Warfighter Interface Division Applied Neuroscience Branch Wright-Patterson Air Force Base, OH 45433	**10. SPONSORING/MONITORING AGENCY ACRONYM(S)** 711 HPW/RHCP/RHCPA
	11. SPONSORING/MONITORING AGENCY REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

DISTRIBUTION STATEMENT A. Approved for public release: distribution unlimited.

13. SUPPLEMENTARY NOTES

88ABW Cleared 03/18/2016; 88ABW-2016-1334; Human Factors and Ergonomics Society 2016 Annual Meeting 19 – 23 Sept 2016

14.

Though not often mentioned, the price point of many eye tracking systems may be a factor limiting their adoption in research. Recently, several inexpensive eye trackers have appeared on the market, but to date little systematic research has been conducted to validate these systems. The present experiment attempted to address this gap by evaluating and comparing five different eye trackers, the Eye Tribe Tracker, Tobii EyeX, Seeing Machines faceLAB, Smart Eye Pro, and Smart Eye Aurora for their gaze tracking accuracy and precision. Results suggest that all evaluated trackers maintained acceptable accuracy and precision, but lower cost systems frequently also experienced high rates of data loss, suggesting that researchers adopting low cost systems such as those evaluated here should be judicious in their research usage.

15. SUBJECT TERMS

Eye tracking, validation, accuracy, precision

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT:**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**	SAR	6	Gregory Funke
Unclassified	Unclassified	Unclassified			**19b. TELEPHONE NUMBER**

WHICH EYE TRACKER IS RIGHT FOR YOUR RESEARCH? PERFORMANCE EVALUATION OF SEVERAL COST VARIANT EYE TRACKERS

Gregory Funke[1], Eric Greenlee[2], Martha Carter[3], Allen Dukes[1], Rebecca Brown[4], Lauren Menke[4]

[1]Air Force Research Laboratory, Wright-Patterson AFB, OH; [2]Texas Tech University, Lubbock, TX;
[3]Miami University, Oxford, OH; [4]Ball Aerospace & Technologies Corporation, Fairborn, OH

Though not often mentioned, the price point of many eye tracking systems may be a factor limiting their adoption in research. Recently, several inexpensive eye trackers have appeared on the market, but to date little systematic research has been conducted to validate these systems. The present experiment attempted to address this gap by evaluating and comparing five different eye trackers, the Eye Tribe Tracker, Tobii EyeX, Seeing Machines faceLAB, Smart Eye Pro, and Smart Eye Aurora for their gaze tracking accuracy and precision. Results suggest that all evaluated trackers maintained acceptable accuracy and precision, but lower cost systems frequently also experienced high rates of data loss, suggesting that researchers adopting low cost systems such as those evaluated here should be judicious in their research usage.

As noted by McCarley and Kramer (2007), eye tracking has been an important source of information about perception and cognition for more than 50 years. It has been utilized to study a diverse number of topics such as the patterns of fixations and saccades while reading text (e.g., Rayner, 1998), the workload of pilots during different phases of flight (e.g., Di Nocera, Camilli, & Terenzi, 2007), and the effectiveness of visual advertisements (e.g., Wedel & Pieters, 2008), among many, many others.

However, research including eye tracking has not been as commonplace as it could be. As noted by Jacob and Karn (2003), eye tracking has remained a very *promising* tool for research, but it has never been as widely utilized as it potentially could be. Those authors provide a cogent treatment of the factors potentially inhibiting wider adoption of eye tracking methodologies, including limitations and challenges associated with eye tracking hardware and software, and with the resultant data related to volume, extraction, and interpretation.

An additional consideration not specifically mentioned by Jacob and Karn (2003) is the cost of an eye tracker. System prices typically scale with hardware capabilities and included software, and may range from thousands to hundreds of thousands of dollars, potentially putting eye trackers beyond the means of many laboratories. However, a few very inexpensive (i.e., less than $1,000 US) eye trackers have begun to appear on the market, such as the Eye Tribe Tracker (theeyetribe.com/), the Tobii EyeX (www.tobii.com/xperience/products/), and the GazePoint GP3 (www.gazept.com/product/gazepoint-gp3-eye tracker/). These systems feature relatively "no frills" hardware and little to no included software.

While these systems offer interested researchers a low cost option for inclusion of eye tracking in their research, few evaluations of the technical capabilities of such systems have been conducted to date (though see Dalmaijer, 2014; Janthanasub & Meesad, in press; and Ooms, Dupont, Lapon, & Popelka, 2015, for limited evaluations of the Eye Tribe Tracker). The purpose for the current evaluation study was to address this gap by examining the capabilities of two low cost trackers, the Eye Tribe Tracker and the Tobii EyeX, compared to two "established" trackers, Seeing Machines faceLAB and Smart Eye Pro, and a new product, Smart Eye Aurora.

METHODS

Participants

In this experiment, 16 people (10 men, 6 women) were recruited from local universities, available Air Force personnel, and the local community. They ranged in age from 20 to 55 (M = 29.75, SD = 9.71). Prospective participant observers were required to have normal or corrected to normal visual acuity. To assess the sensitivity of the examined eye trackers to the presence of eye glasses, 6 of the observers wore their glasses throughout the experiment.

Apparatus

Eye trackers. Five eye trackers were chosen for inclusion in this evaluation study: the Eye Tribe Tracker, Tobii EyeX, Seeing Machines faceLAB, Smart Eye Pro, and Smart Eye Aurora. These five trackers were selected because of their accessibility to our laboratory and because they represent a diverse set of relative price points, from low (Eye Tribe Tracker, Tobii EyeX), to medium (Smart Eye Aurora), and high (Seeing Machines faceLAB, Smart Eye Pro).

All five eye trackers are off-head, optical tracking systems (see Figure 1 for images of the eye tracker layouts). All trackers feature at least two video cameras (Smart Eye Pro was employed using a four camera set up) and at least one infrared emitter. The evaluated trackers operate on the same basic principles, i.e., infrared light reflected from the eye (corneal reflection), eye features such as the pupil, and facial features such as the canthus are used to extract information about point of gaze. More precisely, each system reports the on-screen coordinates that correspond to the estimated point of intersection between the observer's gaze and the visual display (readers interested in a more comprehensive understanding of

the operation of eye trackers are directed to, e.g., Holmqvist et al., 2011).

Each tracker has a specific recording speed, specified in hertz (Hz), which represents the number of gaze estimates the system makes per second. Nearly all of the trackers included in this evaluation record at 60 Hz, with the exception of the Smart Eye Pro, which records at 120 Hz. It is worth noting that the observed recording rates of all systems included in this evaluation were within approximately 1 Hz of the manufacturer specified sampling rates (i.e., each of the evaluated systems' recording rates were very close to those advertised by manufacturers).

Task environment. Due to space constraints associated with deployment of the eye tracking systems, trackers evaluated in this experiment were split between two identical workstations (see Figure 1 for the layout of those systems). At both workstations, task stimuli were presented to observers on 48.26 cm Samsung SyncMaster 940Bx LCD monitors. The monitors were set to a 1280 × 1024 display resolution (display PPCM = 34). Note that each eye tracker was placed according to manufacturer recommendations, and infrared emitters were disabled when the associated system was not in use.

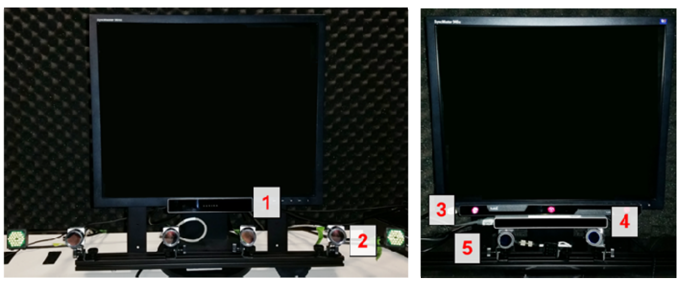

Figure 1. Illustration of the five eye tracker systems deployed at the two work stations. The five trackers are: 1) Smart Eye Aurora, 2) Smart Eye Pro, 3) Tobii EyeX, 4) Eye Tribe Tracker, and 5) Seeing Machines faceLAB.

This evaluation experiment required seven networked PCs. All PCs featured x86 compatible processors and the Windows 7 operating system. Each evaluated eye tracker was connected to a separate PC that ran all associated software and recorded gaze data. An additional PC presented and recorded fixation task events (described below). The final PC was utilized by the experimenter to control the task computer and initialize the appropriate eye tracker before the fixation task began. The experimenter's PC also ran custom software that synchronized system time across all PCs, enabling comparable time stamping across computers.

Procedure

Upon arrival in the laboratory prospective participant observers were required to verbally verify that they had normal or corrected to normal visual acuity, and that they were wearing their corrective lenses if required to do so. Observers were then assigned a random schedule of exposure to each eye tracker system under evaluation.

Next, observers were seated at the appropriate workstation. The seated distance of observers to the monitor varied slightly based on the height of the observer and the specific eye tracker being evaluated. Once an observer was seated at an appropriate distance and height for the tracker, the distance between the observer's eye and the display monitor was recorded. These individualized values were then utilized in calculating all associated visual angles for each combination of observer and eye tracker. Across observers and trackers, the mean seated viewing distance was 70.08 cm.

After being seated, the next step was to calibrate the eye tracker system. Up to four calibration attempts were made for each observer on each eye tracker system. Calibration was considered successful if tracking could be achieved at an average 2° visual angle error or less across the display screen, as reported by the eye tracker's calibration software. If calibration could not be achieved at that level within four attempts that observer was marked as non-trackable for that system and calibration was initiated for the next system according to the observer's assigned schedule.

The calibration procedure for each tracker was mostly similar. Calibration requires observers to gaze at a succession of on-screen points, and based on these data, the eye tracker software attempts to accurately assess the point of gaze-screen intersection. Tobii EyeX, Seeing Machines faceLAB, Smart Eye Pro, and Smart Eye Aurora all employ a 9-point (3 × 3) calibration grid; the Eye Tribe Tracker utilizes a 16-point (4 × 4) grid. Following calibration, each system provides an estimate of tracking *accuracy*, i.e., the degree of error in assessed gaze location (usually specified in degrees visual angle). In addition, the Seeing Machines faceLAB and the Smart Eye Pro and Aurora trackers also provide a measure of the standard deviation associated with calibration accuracy, which is typically referred to as the system's *precision*. However, the specificity of the accuracy metric varied across trackers included in this evaluation.

Specifically, the Tobii EyeX provides only a binary calibration outcome, i.e., "calibrated" or "not calibrated." To ensure that participants met the calibration inclusion criteria described previously, a follow-up "calibration evaluation window" was required. In this software (which was included with the EyeX), the 9-point calibration grid is re-presented with additional, larger circles (roughly 4.25 cm, or 2° visual angle) around each point. Overlaid on this display are real-time gaze location estimates made by the eye tracker. Observers in this evaluation were required to serially gaze at each of the 9 calibration points, and if a preponderance of the real-time estimated gaze locations fell outside the 2° visual angle border, recalibration was initiated.

A bit more sophisticatedly, the Eye Tribe Tracker provides a categorical rating, from 1 to 5, of calibrated accuracy. The ratings, (derived from the manufacturer's website, http://dev.theeyetribe.com/start/), are: 1 – recalibrate; 2 – poor (< 1.5° visual angle error); 3 – moderate (< 1° visual angle error); 4 – good (< .7° visual angle error); 5 – perfect (< .5° visual angle error).

The remaining trackers evaluated provide a numerical estimate of tracking accuracy and precision. The Seeing Machines faceLAB tracker outputs a display-wide average, while the Smart Eye Pro and Aurora each provide separate estimates for each calibration point.

Following successful calibration of a tracker, observers then engaged the fixation task. During this task, fixation crosses, which appeared as 60 point (~1.73° visual angle) Futura Bold "plus" ("+") signs, were displayed on the workstation monitor. Crosses were presented in black (RGB: 0, 0, 0; luminance = .18 cd/m^2) on a gray (RGB: 240, 240, 240; luminance = 93.53 cd/m^2) background. The contrast of the black cross against the gray background based on the Michaelson contrast ratio (maximum luminance – minimum luminance / maximum luminance + minimum luminance; Coren, Ward, & Enns, 1999) was 99.60%.

Crosses were presented serially (only one on the screen at a time) for 3 seconds. The crosses were programmed to appear in a random order at 36 locations on the screen – these locations were determined by dividing the screen into a 6 × 6 grid (see Figure 2 for an illustration). The crosses appeared at the center of each grid rectangle. Observers were instructed to fixate the center of each cross as it was presented on the screen during the fixation task. After the 3 second presentation duration of a cross had elapsed, a new cross was generated at another random location in the grid, with the stipulation that a cross was displayed at each grid location five times during the fixation task. The fixation task was 9 minutes in duration, during which observers viewed a total of 180 fixation crosses.

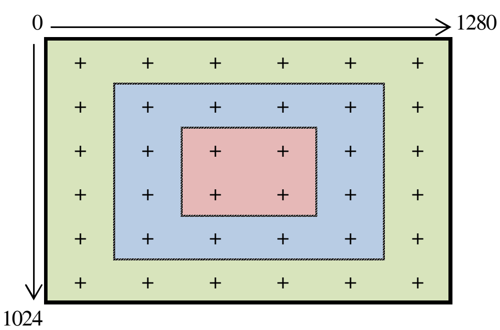

Figure 2. Illustration of the spatial arrangement of the 6 × 6 grid of fixation cross locations during the fixation task. Also depicted are the three screen "zones," center, intermediate, and outer edge, which are presented here bounded by dashed lines and in red, blue, and green, respectively, to facilitate comprehension; the actual fixation task display featured no such screen demarcations.

Observers were free to complete their assigned order of eye trackers at their convenience (i.e., observers were not required to complete the evaluation in a single session). Most observers completed the evaluation across 2-3 sessions.

RESULTS

In presenting the results of our evaluation, we will begin with issues of calibration, and then proceed to data quality, and finally estimates of tracking accuracy and precision.

Calibration Outcomes

The number of attempts required to meet our satisfactory calibration criteria (i.e., calibration resulting in 2° visual angle error or less, as reported by the eye tracker's calibration software) varied between observers and eye tracking systems. In some cases, successful calibration was not achieved, resulting in a reduced sample size for each of the eye tracking systems. Table 1 presents the percentage of observers who could be calibrated on each eye tracker ("Percent calibrated" in the table). To facilitate comprehension, data in the table are presented for observers without glasses ("No glasses"), observers who wore their glasses, and for the total sample ("All observers"). Also presented in the table are the mean numbers of attempts required to achieve successful calibration for each system.

Perusal of Table 1 will reveal that for each eye tracker evaluated, the percentage of successful calibrations is relatively poor for observers with glasses, resulting in a drastically reduced sample size to evaluate tracking quality with glasses. This is not unexpected, however, as the presence of eye glasses may interfere with or distort eye tracking attempts, due to factors such as lens thickness and increased glare (Poole & Ball, 2006).

Gaze Tracking Quality

As mentioned above, each of the eye tracking systems included in the current evaluation provided an estimate of observer gaze location multiple times per second. In addition to gaze location, those estimates also included an indicator of data quality. Such metrics are provided by each system and are essentially qualitative confidence measures based on whether and to what degree the system was "locked on" to critical gaze-related features of an observer necessary for the system to make an accurate estimate of gaze location.

The nature and organization of these quality measures vary from system to system. For most systems, information is provided indicating whether or not the system was able to track a user's gaze, and if so, whether this tracking is based on features from both eyes, a single eye, or the position and orientation of the head alone. For systems that provided this information, we discarded data points for which the system was unable to track the observer's gaze based on both eyes – per the recommendation of most of the eye tracking system manufacturers. The Smart Eye Aurora system did not provide an absolute quality value indicating whether both eyes could be tracked, so we discarded data points during which head tracking was lost. Table 1 presents the percentage of usable data for each system remaining after data points of insufficient quality were discarded ("Percent usable data" in the table).

Examination of Table 1 suggests that the low cost Eye Tribe Tracker and the Tobii EyeX experienced more frequent data quality problems than the other, more costly trackers evaluated, resulting in substantially fewer usable gaze estimate data points.

Gaze Tracking Accuracy & Precision

Calibrated accuracy and precision. As mentioned previously, following calibration, each of the evaluated eye tracking systems provided a measure of calibration accuracy. In addition, the Seeing Machines faceLAB and the Smart Eye Pro and Aurora trackers also provided measures of precision. These values represent the manufacturer's best estimate of the

Table 1. Performance of each evaluated eye tracking system.

	Tracking System				
Evaluated Factors	Eye Tribe Tracker	Tobii EyeX	Seeing Machines faceLAB	Smart Eye Pro	Smart Eye Aurora
No glasses					
Percent calibrated	90.00%	90.00%	80.00%	100.00%	70.00%
Mean cal. attempts	1.75	1.00	1.29	1.60	1.86
Percent usable data	77.99%	76.02%	88.17%	100.00%	99.86%
Cal. angular error	< 0.70° [1]	< 2.00° [1]	1.07°	0.96°	0.48°
OAE: Whole screen	1.30°	1.05°	2.40°	1.93°	1.70°
OAE: Center	1.22°	0.93°	2.65°	1.37°	1.27°
OAE: Intermediate	1.29°	0.96°	2.49°	1.74°	1.49°
OAE: Outer edge	1.32°	1.14°	2.30°	2.15°	1.91°
Cal. precision	N/A[2]	N/A[2]	0.84°	1.15°	0.34°
OP: Whole screen	1.04°	0.67°	1.41°	1.21°	1.20°
OP: Center	0.61°	0.58°	1.29°	0.89°	0.99°
OP: Intermediate	0.87°	0.59°	1.34°	1.04°	1.07°
OP: Outer edge	1.23°	0.73°	1.47°	1.38°	1.32°
Glasses					
Percent calibrated	0.00%	50.00%	33.33%	66.66%	16.67%
Mean cal. attempts	N/A[3]	1.67	1.50	1.33	3.00
Percent usable data	N/A[3]	84.32%	97.00%	100.00%	99.95%
Cal. angular error	N/A[3]	< 2.00° [1]	1.10°	0.83°	0.58°
OAE: Whole screen	N/A[3]	1.44°	1.25°	1.44°	1.50°
OAE: Center	N/A[3]	1.15°	1.22°	1.09°	0.95°
OAE: Intermediate	N/A[3]	1.30°	1.23°	1.38°	1.48°
OAE: Outer edge	N/A[3]	1.58°	1.27°	1.54°	1.63°
Cal. precision	N/A[2]	N/A[2]	0.73°	1.37°	0.43°
OP: Whole screen	N/A[3]	0.85°	0.66°	1.17°	1.16°
OP: Center	N/A[3]	0.62°	0.72°	1.09°	0.52°
OP: Intermediate	N/A[3]	0.89°	0.73°	1.26°	1.20°
OP: Outer edge	N/A[3]	0.88°	0.61°	1.14°	1.26°
All observers					
Percent calibrated	56.25%	75.00%	62.50%	87.50%	50.00%
Mean cal. attempts	1.75	1.18	1.33	1.52	2.00
Percent usable data	77.99%	78.29%	89.94%	100.00%	99.87%
Cal. angular error	< 0.70° [1]	< 2.00° [1]	1.07°	0.92°	0.49°
OAE: Whole screen	1.30°	1.16°	2.17°	1.79°	1.68°
OAE: Center	1.22°	0.99°	2.36°	1.29°	1.23°
OAE: Intermediate	1.29°	1.05°	2.24°	1.64°	1.49°
OAE: Outer edge	1.32°	1.26°	2.09°	1.98°	1.87°
Cal. precision	N/A[2]	N/A[2]	0.82°	1.21°	0.35°
OP: Whole screen	1.04°	0.72°	1.26°	1.20°	1.20°
OP: Center	0.61°	0.59°	1.17°	0.95°	0.93°
OP: Intermediate	0.87°	0.67°	1.22°	1.10°	1.09°
OP: Outer edge	1.23°	0.77°	1.30°	1.31°	1.32°

Note. OAE = observed angular error; OP = observed precision.

[1]The Eye Tribe Tracker and Tobii EyeX provide a categorical, rather than quantitative measure of calibration accuracy. Please see the Procedure section for further information.

[2]The Eye Tribe Tracker and Tobii EyeX do not provide estimates of precision.

[3]As no participants with glasses could be calibrated in this evaluation, these data cannot be presented.

margin of error in their gaze location discriminations. To facilitate comparisons with *observed accuracy* and *observed precision* measures, Table 1 presents the mean, display-wide system-reported, "calibrated" error and precision estimates (for those systems that output such values).

Observed accuracy and precision. After removing data points of insufficient quality, the gaze-tracking record was overlaid with the corresponding stimulus timing record from the fixation task. The pairing of these records produced an event-related log of gaze tracking, which was then used to evaluate tracker accuracy and precision.

While the fixation task involved immediate shifts of the fixation cross, gaze redirection takes time (approximately 100 ms; Andreassi, 2007), and inclusion of such saccadic behavior would contaminate any estimate of gaze fixation. To control for this, the analysis of gaze tracking was limited to the central second of each 3-second stimulus presentation. For each sample in this 1-second window, we determined the Euclidean distance between the assessed gaze location and the center of the presented fixation cross. We then computed the mean difference for each observer and tracker at each of the 36 fixation cross locations as an index of observed accuracy. The standard deviation (i.e., precision) of these values was also computed for each stimulus. Both accuracy and precision values were then converted to degrees visual angle, calculated using each individual's measured viewing distance.

As a final consideration, the accuracy and precision of eye tracking systems typically degrades near the edges of the screen. To further elucidate eye tracker accuracy in our evaluation, we examined how distance from the center of the screen affected eye tracking performance. We accomplished this by dividing the screen into three concentric "zones," corresponding to the center, the intermediate, and the outer edge of the screen. Figure 2 depicts these regions as they relate to the fixation task display.

In assessing observed tracker accuracy and precision, it should be noted that the data collected from four observers was excluded from those calculations. Specifically, three observers were judged to have outlier accuracy scores (i.e., greater than 2.5 *SD* from the mean), but only for a single eye tracker each; the associated systems were the Eye Tribe Tracker, Seeing Machines faceLAB, and the Smart Eye Pro. A final observer's Tobii EyeX data had to be excluded because of a software error that prevented common timestamping across data sources. In all cases, data were only excluded from estimates of observed accuracy and precision, and only for the specific systems affected.

Table 1 provides the mean observed accuracy and precision for each eye tracker for the whole screen and in each of the three screen zones. Generally speaking, error increased and precision decreased the further the fixation cross was presented from the center of the screen. In addition, comparisons of calibrated and observed accuracy and precision reveal that, generally, the evaluated eye tracking systems were more imprecise than calibrated estimates suggested.

DISCUSSION

Ultimately, it is our hope that this evaluation study will serve other scientists as they consider their choices regarding the acquisition and use of eye tracking systems for research

and psychophysiological monitoring applications. A key consideration for such decisions may be the ability of each system to be successfully calibrated with different individuals. While the SmartEye Pro was the most expensive of the tested systems, it also appears to have had the highest rate of successful calibrations. In experimental settings, failures to calibrate represent an exclusionary criterion, a screen for study participation that reduces the proportion of the population that may be sampled for study. In applied settings, failures to calibrate may be even more problematic, as they may prohibit psychophysiological monitoring and any human-in-the-loop systems that require such monitoring.

Another consideration in the selection and use of eye tracking systems may be tradeoffs between price and tracking performance, which are made apparent by the current study. While the degree of error and precision of the most affordable systems are comparable to the most expensive systems, the less expensive systems also produced a greater proportion of low quality, unusable data. Though not directly considered in this evaluation, such missing data can artifactually influence estimates of the number and duration of fixations, saccadic rates, and blinks, all of which are measures that may be of interest to many human factors professionals (Holmqvist, Nystrom, & Mulvey, 2012). While this may limit the overall utility of such trackers, there are likely applications for which the missing data would be less problematic. For example, for a researcher interested in relative dwell time across several areas of interest in a visual display, the low cost eye trackers might be sufficient despite the likely high degree of unusable data.

It is also worth noting that each of the eye trackers differs in terms of the capabilities of the included software. Generally speaking, more expensive systems are packaged with software that can be used to filter and process data, while the less expensive systems depend on the user to generate and apply their own algorithms. Additionally, some information cannot be obtained through the use of the most inexpensive eye trackers. For example, tracking and detection of eyelid behavior (e.g. blinks, PERCLOS) was not a feature of the software provided with the Eye Tribe Tracker and the Tobii EyeX.

When selecting an eye tracker for either research or application purposes, we advise careful consideration of the relative strengths and weaknesses of the systems. The eye trackers examined here represent only a sample of the available choices. It is crucial that researchers continue to examine the capabilities and accuracy of eye tracking systems in order to determine the validity of the measures that each system provides. Future research should extend to other eye tracking systems, non-gaze behaviors (e.g. eyelid behavior, pupillometry), and should examine the effects of calibration drift (i.e., decreases in tracking accuracy over time) and head movements on system performance.

REFERENCES

Andreassi, J.L. (2007). *Psychophysiology: Human behavior & physiological response* (5th ed.). New York, NY: Psychology Press.

Coren, S., Ward, L.M., & Enns, J.T. (1999). *Sensation and perception* (5th ed.). Fort Worth, TX: Harcourt-Brace.

Dalmaijer E. (2014). Is the low-cost Eye Tribe eye tracker any good for research? *PeerJ PrePrints*, 2:e585v1. Retrieved from https://doi.org/10.7287/peerj.preprints.585v1

Di Nocera, F., Camilli, M., & Terenzi, M. (2007). A random glance to the flight deck: Pilot's scanning strategies and real-time assessment of mental workload. *Journal of Cognitive Engineering and Decision Making, 3*, 271–285.

Holmqvist, K., Nyström, M., Andersson, R., Dewhurst, R., Jarodzka, H., & van de Weijer, J. (2011). *Eye tracking: A comprehensive guide to methods and measures*. Oxford, United Kingdom: Oxford University Press.

Holmqvist, K., Nyström, M., & Mulvey, F. (2012, March). *Eye tracker data quality: What it is and how to measure it*. Paper presented at the 2012 ACM Symposium on Eye Tracking Research and Applications, Santa Barbara, CA.

Jacob, R.J., & Karn, K.S. (2003). Commentary on section 4. Eye tracking in human-computer interaction and usability research: Ready to deliver the promises. In J. Hyönä, R. Radach, & H. Deubel (Eds.), *The mind's eye: Cognitive and applied aspects of eye movement research* (pp. 573-607). New York, NY: North Holland.

Janthanasub, V., & Meesad, P. (in press). Evaluation of a low-cost eye tracking system for computer input. *KMUTNB International Journal of Applied Science and Technology*. Retrieved from http://dx.doi.org/10.14416/j.ijast.2015.07.001

McCarley, J.S., & Kramer, A.F. (2007). Eye movements as a window on perception and cognition. In R. Parasuraman & M. Rizzo (Eds.), *Neuroergonomics: The brain at work* (pp. 95-112). New York: Oxford University Press.

Ooms, K., Dupont, L., Lapon, L., & Popelka, S. (2015). Accuracy and precision of fixation locations recorded with the low-cost Eye Tribe tracker in different experimental set-ups. *Journal of Eye Movement Research, 8*, 1-24.

Poole, A., & Ball, L.J. (2006). Eye tracking in human-computer interaction and usability research: current status and future prospects. In C. Ghaoui (Ed.), *Encyclopedia of human computer interaction* (pp. 211-219). Hershey, PA: Idea Group Reference.

Rayner, K. (1998). Eye movements in reading and information processing: 20 years of research. *Psychological Bulletin, 124*, 372-422.

Wedel, M., & Pieters, R. (2008). A review of eye tracking research in marketing. *Review of Marketing Research, 4*, 123-147.